TOPEX/Poseidon Orbit Transfer Maneuver (TOTM) Design and Mission Operation

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ABSTRACT

The TOPEX/Poseidon orbit transfer maneuver (TOTM) design and mission operation are summarized herein. TOPEX/Poseidon is a joint US-French program for the study of Earth's ocean topography. The JASON-1 satellite is a follow-on mission to continue the TOPEX heritage by repeating the same ground track pattern. After the calibration and validation phase of JASON-1 in which the two satellites were maintained in the same orbit plane, in order to provide new science investigation opportunities, TOPEX was required to perform maneuvers to bring it midway between two adjacent JASON-1 tracks. Frozen orbit conditions must be reinstated after acquiring the new reference ground track pattern.

The TOTM design phase consisted of a feasibility analysis on cost, a preliminary trade study on delta-V requirements, and detailed analyses and design of the baseline burn sequence. The retro-burn centroid times were optimized to achieve frozen orbit conditions in the final orbit. All designs and analyses were supported and verified with high-fidelity simulations using the JPL Double Precision Trajectory (DPTRAJ) software.

The TOTM mission operation extended from August 15, 2002 to September 16, 2002. Three posigrade and three retrograde maneuvers were executed. Maneuver execution errors were compensated for by tweaking and optimizing subsequent burns based on the ground track spacing and drift rate determined from tracking data. All the mission objectives were achieved. The TOPEX/Poseidon satellite successfully acquired a new orbit which repeats ground tracks midway between two adjacent JASON-1 tracks, and frozen orbit was reinstated.

INTRODUCTION

Motivations and Objectives

The TOPEX/Poseidon satellite, launched on August 10, 1992, is in its 11th year of successful operation. The TOPEX/Poseidon mission, a joint US-French program, conducted by the National Aeronautics and Space Administration (NASA) and the Centre National d'Etudes Spatiales (CNES) studies and gathers information about the world's oceans to better understand ocean circulation, its interaction with the atmosphere, to improve our knowledge of climate change and heat transport in the ocean, and to study the marine gravity field.

JASON-1 satellite, a follow-on mission conducted by the same organizations, was launched into orbit on December 7, 2001. Like TOPEX/Poseidon, it is an oceanography mission to further monitor global ocean circulation, discover the ties between the oceans and the atmosphere, improve global climate prediction, and monitor events such as El Nino conditions and ocean eddies. During the calibration & validation phase, JASON-1 was maintained in an orbit plane close to the orbit plane of TOPEX/Poseidon. The time phase between the two satellites was about 72 seconds, and they repeated the same ground track in order to cross-calibrate JASON-1's and TOPEX/Poseidon's performance. TOPEX/Poseidon and JASON-1 fly at an altitude of about 1336 km in a nearly circular orbit, with an inclination of 66.04°. This orbit provides for an exact repeat ground track every 127 revolutions (about ten days per cycle).

Originally planned was the decision to keep JASON-1 in the same ground track as TOPEX/Poseidon during the first 6 months of routine operations (Calibration/Validation phase). After the CAL/VAL phase, it was expected that the orbit of the older TOPEX/Poseidon satellite will be changed such that its new ground track will be in between two adjacent JASON-1 ground tracks. Such a "tandem" configuration provides an unprecedented and cost-effective opportunity to obtain spatially-separated measurements and conduct new oceanic science investigations.

Early Design and Feasibility Analysis

The goal of the tandem mission phase is to provide possible unprecedented opportunities for oceanographic studies by using the two high-precision altimeters onboard the two satellites. Earlier study and analysis were done on the tandem mission phase by looking at maneuvering the TOPEX satellite to acquire a new orbit to establish an orbit phasing to meet science requirements. Two main options for TOPEX future orbit were investigated. One option was to move TOPEX ground track grid sidewise (east or west of pre-TOTM ground track) to an interleaving track, and the other option was to keep it on the same ground track grid with an integer number of days offset to JASON-1 (one to five days time offset). The conclusion/recommendation of the Science Working Team was to move TOPEX to an interleaved orbit, which would make TOPEX trace a ground track in between two adjacent JASON-1 ground tracks. The TOPEX Project adopted that recommendation. That would require shifting the orbit by at least 1.4° or 157.8 km at the equator crossing track. This is accomplished by keeping the two satellites in the same orbit plane, but at different points in the orbit (different true anomaly) and not necessarily changing the orbit plane. Since there was no strong scientific desire as indicated by the Science Working Team to specify certain time offset between the two satellites equatorial crossing times and duration of phasing, time offset and duration of phasing were to be determined by satellite constraints and issues. Figure 1 shows the result of the study of the cost of phasing the TOPEX orbit for the tandem mission. It relates the Δv required with the duration of phasing for the single integer number of days offset case (same ground track grid with offset) as well as the 1.4° longitude at equator spacing. In the single integer number of days offset case, the true anomaly phase shifts, +/-36, +/-72, +/-108, +/-144, +/-180 degrees, represent adjacent tracks over-flown on days 8, 5, 2, 9, 6 of the 10-day cycle for positive phasing. Negative true anomaly phasing represents tracks over-flown on days 4, 7, 10, 3, 6 of the 10-day cycle.

The approved 1.4° longitude spacing case is shown in the figure as curves of true anomaly phase shifts of +/-18, +/-54, +/-90, +/-126, and +/-162 degrees. Increasing the duration of phasing would help to reduce the total Δv required as follows:

- One cycle (10 days): about 2, 6, 9, 13, 17 m/sec
- Two cycles (20 days): about 1, 3, 5, 7, 8 m/sec
- Three cycles (30 days): about 1, 2, 3, 5, 6 m/sec

As a result of the TOPEX satellite issues and constraints, a phase shift of 18° was chosen (TOPEX and JASON-1 separated by 18° in true anomaly). This provides the lowest Δv required to place TOPEX in the tandem mission with JASON-1. Based on this study, the total Δv required was approximated as follows:

- One cycle: about 2 m/sec
- Two cycles: about 1 m/sec
- Three cycles: less than 1 m/sec

The above Δv is the sum of two ΔVs of equal value. The first is to change the semi-major axis (sma), or period, to start a drift relative to JASON-1 track and the second to stop the drift (restore sma) at 1.4° equatorial longitude spacing.

Since all maneuvers to change the orbit were semi-major axis maneuvers, there were no significant satellite/navigational issues except for the inherent risk of doing large maneuvers (Orbit Maintenance Maneuvers are in mm/sec only). Currently, TOPEX has about 200 kg of propellant (187 m/sec Δv). So, the issue was not resources but using satellite sub-systems not normally executed, and/or beyond limits seen in normal operations. The plan was to use 1-N thrusters to accomplish the orbit transfer maneuvers.

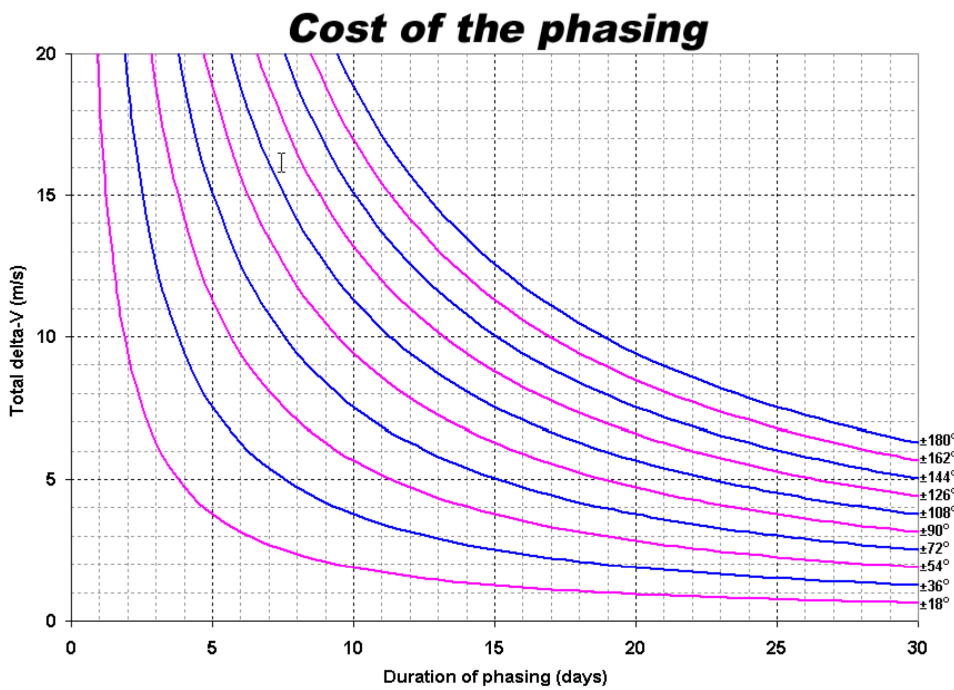

Figure 1. The Cost of Orbit Phasing

CURRENT TOPEX REFERENCE ORBIT

During the calibration/validation phase, TOPEX and JASON-1 traced the same ground track. The TOPEX/JASON-1 ground track consists of 127 cycles (254 passes), and repeats every 9.91564 days. The average difference between adjacent tracks is about $360^{o}/127=2.83^{o}$ or 315.55 km. JASON-1 led TOPEX by approximately 72 sec in equator crossing. The table below shows the TOPEX reference orbit parameters:

Table 1. TOPEX Reference Orbit Parameters

Semi-major axis (km)	7714.42938
Eccentricity	0.000095
Inclination (deg)	66.039
Period (sec)	6745.72
Inertial Node Rate (deg/day)	-2.0791
Cycle Duration (days)	9.9156

TARGET TANDEM ORBIT

The TOTM sequence should accomplish several goals and objectives. In addition to raising TOPEX sma by about 1 km with posigrade burns to begin drift, and then lowering sma by the same amount with retrograde burns to stop drift, both the eccentricity and the argument of perigee must be maintained to the desired frozen values after acquiring the new orbit. It must also acquire the new desired reference ground track pattern (the new TOPEX ground track and the ± 1 km control band).

To achieve the target tandem orbit for TOPEX, the following design requirements/constraints were identified:

1) Use of 1-N thrusters only
2) No out-of-plane maneuvers
3) Perform all the necessary retro burns during the fixed yaw flying backward (Yaw=180°) attitude period
4) Achieve frozen status in final orbit

After the final burn is performed and TOPEX is in its new orbit, the difference in equator crossing time of the TOPEX and JASON-1 will be almost 7 minutes, with JASON-1 the leading satellite.

PRELIMINARY TRADE STUDY ON ΔV REQUIREMENTS

In the beginning stages of the design, estimates of the required total Δv and different options for burn separations and magnitudes were made. These estimates were based on elementary equations of orbital mechanics where the effects of various perturbations such as corrections to gravitational field, atmospheric drag, solar radiation pressure, etc. were neglected. The organization of this section is as follows. First, the effect of Δv on drift rate (of TOPEX ground track with respect to reference), change in semi-major axis and eccentricity are reviewed. Then the preliminary trades are presented.

Drift Rate and Delta-V

A satellite's ground track will drift when its orbital period is changed. Before any maneuvers TOPEX and JASON-1 are on the same ground track. After the orbital period of TOPEX is increased by a fixed value, its ground track will start to drift at a constant rate to the west. In order to quantify the relationship between the drift rate and change in the period, one has to first consider the change in the mean anomaly or phase difference between TOPEX and the reference (JASON-1) orbit as a function of time:

$$\Delta\Phi(t) = 2\pi\left(\frac{1}{T}-\frac{1}{T_R}\right)t \tag{1}$$

where ΔΦ(t) is the phase difference in radians, T and T_R are the "new and reference periods respectively. As a result of the Earth's rotation and the nodal regression (rotation of the orbital plane), the drift in radians is related to the phase difference by:

$$\Delta\lambda = T_R\left(\frac{\omega_e+\overset{\circ}{\Omega}}{2\pi}\right)\Delta\Phi$$

where ω_e is the Earth's rotation rate and $\overset{\circ}{\Omega}$ is the nodal regression rate.

Combining the above equations the following relation between drift rates as a function of change in the period of the orbit is obtained:

$$\Delta\dot{\lambda} = T_R\left(\frac{\omega_e+\overset{\circ}{\Omega}}{2\pi}\right)\Delta\dot{\Phi} = T_R\left(\frac{1}{T}-\frac{1}{T_R}\right)\left(\omega_e+\overset{\circ}{\Omega}\right) \tag{2}$$

It is assumed that the maneuver takes place at perigee ($r_0 = (1-e_0)a_0$), along the orbit. Using this assumption the new semi-major axis after the burn becomes:

$$a_1 = \frac{r_0}{2-\dfrac{(v_0+\Delta v)^2 r_0}{\mu}} \tag{3}$$

From the post-burn semi-major axis, the new period can be computed. By inserting the post-burn semi-major axis in Equation (2), the drift rate can be computed. In this estimation, the duration of the maneuver was not considered. These equations were programmed in a spreadsheet to compute the required ΔV's to achieve different changes in the drift rates. As the following plots (Figure 2 and Figure 3) show, the change in the drift rate is almost linear in ΔV and the required ΔV to achieve the desired drift varies inversely proportional to time. The change in the drift rate following a maneuver is approximately:

$$\Delta\overset{\circ}{\lambda}(\text{deg/sec}) \approx -\frac{3a\text{V}}{\mu}(\omega_e+\dot{\Omega})\Delta\text{V} = \text{-1.734238E-06 }\Delta\text{V(m/s)}$$

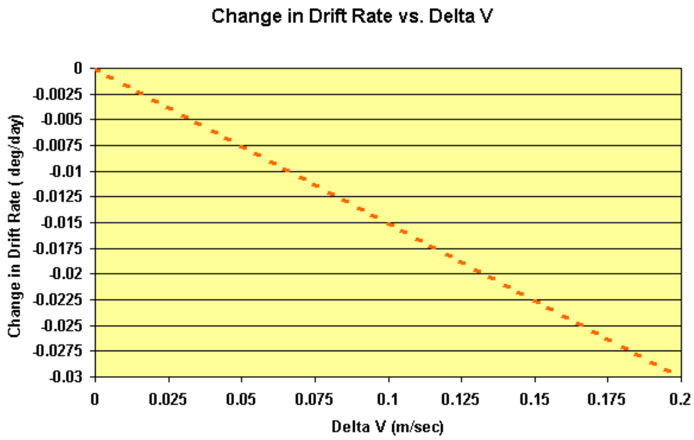

Figure 2. Estimated Change in Drift Rate vs. Delta-V

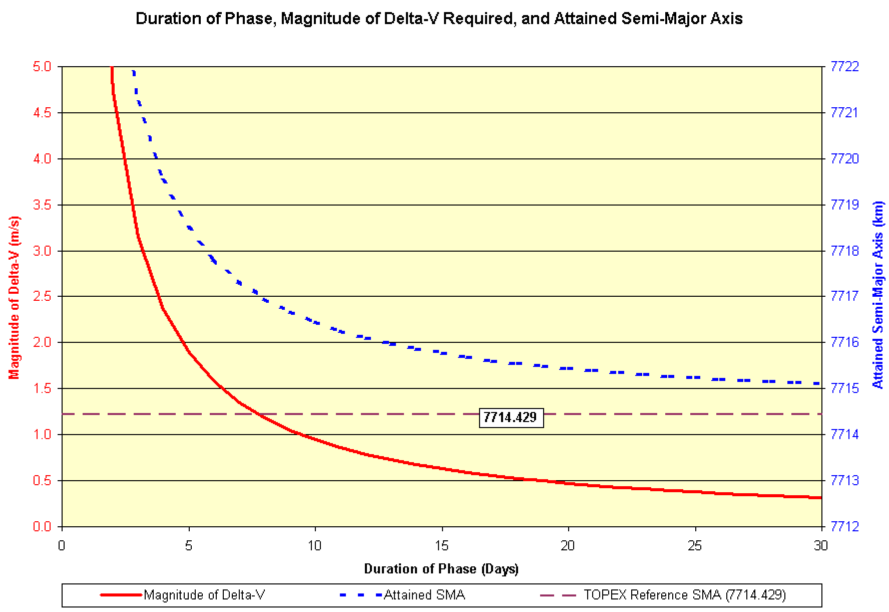

Figure 3. Duration of Phase, Magnitude of Delta-V Required, and Attained Semi-Major Axis

Preliminary Trades

In the preliminary trades, options for different burn separations with two maneuver spacing were studied: one to start the drift and one to stop drift. The table below summarizes the results.

Table 2. Preliminary Trade Study of Estimated Δv Requirement vs. Mission Duration

Maneuver Options	*Drift Rate*	*Delta-V Magnitude*	*Number of Maneuvers*	*Maneuver Spacing*
1 Cycle (10 Days)	-0.142 deg/day	0.946 m/s	2	10 days
2 Cycles (20 Days)	-0.071 deg/day	0.473 m/s	2	20 days
3 Cycles (30 Days)	-0.047 deg/day	0.315 m/s	2	30 days

DPTRAJ Runs

Analytical results were verified using the DPTRAJ software. The DPTRAJ input namelist included all small perturbations, as in orbit determination (OD) during normal operations, notably gravitational model perturbations, Earth's tides, solar pressure, atmospheric drag, and a 20 x 20 gravity field.

DPTRAJ simulations, with the applied ΔVs estimated from the analytical equations, yielded ground track spacing at the end of different drift durations as listed in the table below. The total Δv (start and stop drift burns) requirement for 1, 2, and 3 cycles of drift period are approximately 1.892, 0.946, and 0.630 m/s, respectively. Based on the total Δv requirement, it was concluded that a 3-cycle mission duration is preferable.

Table 3. DPTRAJ Results for Trade Study on Total Δv Requirement vs. Mission Duration

Maneuver Options	Estimated Drift Rate (deg/day)	Δv per Burn (m/sec)	Ground Track Spacing at End of Drift (km)
1 Cycle (10 days)	-0.142	0.946	155.5
2 Cycles (20 days)	-0.071	0.473	154.8
3 Cycles (30 days)	-0.047	0.315	153.9

ANALYSIS ON THE EFFECTS OF ΔV ON ORBIT WITH POINTING ERRORS INCLUDED

The A4/C4 thruster pair was designated the source of propulsion for all the orbit transfer maneuvers. The thrusters were fixed relative to the body frame, and the spacecraft would be oriented such that the body frame coincided with the velocity frame before initiating a burn; e.g., nominal Δv would be along the velocity vector. The intention was for the body frame to remain coincident with the velocity frame during the burn for an in-plane maneuver. However, a slight imbalance existed in the coupled thrusters such that a small torque would be generated during a burn. Since the attitude control system (ACS) would be turned off during the burn, any misalignment between the two frames induced by the torque would go uncorrected. The pointing errors on the thrust vector resulting from the open-loop response were deterministic as described in (ref. 1). The pointing errors would cause a loss of Δv along the velocity vector. In addition, the out-of-plane component of Δv resulting from the pointing errors would have an unwanted effect on the orbital elements. Thus, an analysis was conducted to evaluate the impact of predicted pointing errors on the burn performance and orbital elements.

Effects of Pointing Errors on Burn Performance

The component of Δv along the velocity vector is:

$$\Delta v_t = a\int_0^t \cos\gamma(\tau)\cos\psi(\tau)d\tau$$

where a is the thrust acceleration, γ is the pitch angle, and ψ is the yaw angle. If the burn time was small such that the pitch and yaw errors were small and the assumptions $\cos\gamma = 1$ and $\cos\psi = 1$ held true, then it could be approximated that there would be no loss of Δv along the velocity vector due to pointing errors.

For example, a Δv of 0.2 m/sec would require a burn time of 241.6 sec. At the end of the burn, the pitch and yaw errors accumulated would be –4.1179° and 2.1593°, respectively. This satisfied the assumptions $\cos\gamma = 1$ and $\cos\psi = 1$, and thus it could be approximated that the full 0.2 m/sec would be delivered along the velocity vector.

Effects of Δv on Orbital Elements with Pointing Errors Included

From (ref. 2), the analytical equations to calculate the changes in mean orbital elements induced by velocity changes are:

$$\Delta a = \frac{2}{n}\left[\Delta v_r \frac{e\sin f}{\sqrt{1-e^2}} + \Delta v_t \frac{a}{r}\sqrt{1-e^2}\right] \tag{4}$$

$$\Delta e = \frac{\sqrt{1-e^2}}{na}\left[\Delta v_r \sin f + \Delta v_t \frac{a}{er}\left(1-e^2-\frac{r^2}{a^2}\right)\right] \tag{5}$$

$$\Delta i = \Delta v_n \frac{r\cos u}{na^2\sqrt{1-e^2}} \tag{6}$$

$$\Delta \Omega = \Delta v_n \frac{r\sin u}{na^2\sqrt{1-e^2}\sin i} \tag{7}$$

$$\Delta \omega = -\frac{\sqrt{1-e^2}}{nae}\left[\Delta v_r \cos f - \Delta v_t\left(1+\frac{r}{a\left(1-e^2\right)}\right)\sin f + \Delta v_n \frac{re\cot i\sin u}{a\left(1-e^2\right)}\right] \tag{8}$$

$$\Delta M = \frac{\left(1-e^2\right)}{nae}\left[\Delta v_r\left(\cos f - \frac{2re}{a\left(1-e^2\right)}\right) - \Delta v_t\left(1+\frac{r}{a\left(1-e^2\right)}\right)\sin f\right] \tag{9}$$

where: a, e, i, Ω, ω, M = the classical orbital elements
r = radial distance of satellite
u = argument of latitude (= $\omega + f$)
f = true anomaly
n = orbit rate

The effects of a commanded Δv of 0.15 m/sec with pointing errors on the mean orbital elements were dependent on the position in the orbit at which the maneuver was executed. The changes are given in Table 4.

Table 4. Effects of 0.15 m/sec Δv with Pointing Errors on the Mean Orbital Elements

Orbital Element	Maximum Change	Minimum Change
Semi-major axis (m)	321.99	321.96
Eccentricity	4.17E-05	-4.17E-05
Inclination (deg)	8.45E-06	-8.45E-06
Argument of Ascending Node (deg)	1.24E-04	-1.24E-04
Argument of Perigee (deg)	28.66	-28.66
Mean anomaly	28.66	-28.66

The changes in the sma were for orbit-shaping purposes, to achieve the differential orbit rate needed for arriving at the target in-plane phasing desired between the 2 satellites. The changes in the eccentricity and argument of perigee could take the orbit out of the frozen condition, which was acceptable since there was no requirement for the orbit to remain frozen during the drift. Of the orbital elements, only the change in inclination was of concern. Due to pointing errors, the out-of-plane component of a commanded Δv of 0.15 m/sec was 0.001 m/sec, which would cause a change of less than 9×10^{-6} deg in inclination for the worst case. Referring to the variations of mean inclination seen in the past during normal operation from 1999 to present (ref. 5), the range extended from 66.0372° to 66.044°, a delta of 0.0068°. The worse case change in inclination would be well within the bounds and thus was acceptable. Furthermore, compensation for the pointing errors would be incorporated into the design of the burns. Therefore, it could be assumed that the undesirable effects of the pointing errors on the mean orbital elements would be greatly reduced and thus negligible.

TRADE STUDY ON BURN SEPARATION

The executions of the retro burns were constrained to a 10-day window of fixed yaw, flying backward mode extending from 10-Sep-02 to 20-Sep-02. To maximize the time available for contingency maneuvers following the last burn, it was desirable to complete all the retro burns as early as possible in the 10-day window. However, decreasing the time separation between burns would also reduce the tracking time and data necessary for OD. Thus, an analysis was done to evaluate the trade-offs between burn separation and OD accuracy.

A conservative assumption was made that one full day would be needed for performing post-burn processing and analysis, during which the Navigation team (NAVT) would re-design the next Δv for error compensation, the Δv would be communicated to the spacecraft team, and commands would be uplinked to TOPEX, etc. Thus, the tracking time would be less than the burn separation by at least one day.

After a burn was executed, the continuous stream of tracking data would allow the OD solutions to converge, which would lead to an accurate determination of the achieved Δv. The achieved Δv would differ from the commanded Δv due to non-deterministic errors in the propulsion system. This error was the maneuver execution error. In the past OMMs, the NAVT 89 to 96 hr (4 days) converged OD solutions had been posted officially as the achieved Δv. With reduced tracking data, the Δv determined from premature OD solutions would contain both known and unknown errors. The unknown error was part of the measurement and estimation process, in the OD solution which had yet to converge. Its significance was reduced as more tracking data became available, until it was assumed negligible upon OD convergence. Thus, the maneuver execution percent error was independent of the maneuver size and was only a function of the tracking time. Thus, the unknown %error was the maneuver estimation error. Compensation for the known Δv error can be made by adjusting the subsequent burns. However, the unknown Δv error would remain unaccounted for and was acceptable only if the magnitude were small. Note that during mission operation, the NAVT OD results would be the primary source of OD solutions with the EPV (from FDF) as a secondary reference. In addition, the GPS fast OD would be used for quick, initial post-burn analysis, regardless of the burn separation.

Trade Analysis on Burn Separation

The standard deviations of the unknown Δv %errors for 2, 3, and 4-day burn separations are listed in Table 5. Note that the GPS fast ODs were 5 to 10 hr solutions for the 2-day burn separation. For the 4-day burn separation, the GPS + SLR OD were 30 hr solutions, and the SLR OD were 72 hr solutions.

Table 5. Standard Deviations of Unknown Δv %Errors

Burn Separation (days)	Tracking Time (hrs)	NAVT OD (%)	FDF OD (%)	GPS Fast OD (%)	GPS + SLR (%)	SLR (%)
2	≤ 24	6.471	8.085	4.213	-	-
3	≤ 48	0.819	4.008	-	-	-
4	≤ 72	0.328	3.723	-	2.985	2.534

Table 5 shows that an increase in the burn separation from 2 to 3 days yielded noticeable improvement. The 1-σ unknown Δv error was reduced from 6.471% to 0.819%. However, not much was gained by increasing the burn separation from 3 to 4 days, which yielded a small reduction of 0.819% to 0.328%. Note that larger burn separations would allow fewer opportunities for the retro burns during the 10-day window. Also, larger burn separations would have fewer days available for contingency maneuvers following the last retro burn.

Conclusions from Burn Separation Trade Study

The only constraint to impact the posigrade burns was that there would be no burns before 15-Aug-02 due to high beta prime angle. After 15-Aug-02, the beta prime angle was acceptable but still high, and the spacecraft would be required to go through large turning angles in the execution of the turn-burn-turn maneuver. Since TOPEX was an old spacecraft, it was essential to minimize the number of posigrade burns for spacecraft issues.

After the calibration burn, 4 days would be needed to perform a thorough analysis to verify and calibrate the predictions on thruster performance. A precise tweaking of the last posigrade Δv was critical in order to achieve the desired drift rate for the succeeding long drift period. Thus, accurate OD solutions following the first and second posigrade burns were required. The long drift period following the third posigrade burn would yield an accurate OD solution as a by-product.

The first retrograde maneuver would be large and would be split into multiple burns, one orbit apart. Rather than evaluating the multiple burns individually, the effect of the total Δv would be analyzed. Precise tweaking was needed in the last two retro maneuvers. Thus, accurate OD solutions following the first and second retro burns were required. Under nominal operation, adequate spacing between the last retro burn and the first OMM was expected such that an accurate OD solution would be available for the planning of the first OMM.

For the retrograde burns, a 10-day window was allowed for the execution of all the maneuvers. Thus, it was desirable to minimize the burn separation in order to allow more time for contingencies following the last burn. By increasing the burn separation from 2 to 3 days, the time available for contingency maneuvers following the last retro burn would be reduced from 6 to 4 days. However, the 1-σ unknown Δv error was also reduced from 6.471% to 0.819%, a level that could be comfortably assumed as negligible. Also, increasing the burn separation would allow more time to tweak and plan for the next maneuver. Thus, it was deemed as worthy of a trade.

In conclusion, the first burn would be executed on 15-Aug-02, and the time separation for the posigrade burns would be 4 days to allow accurate OD solutions. For the retrograde burns, the maneuvers would be 3-days apart, to allow fairly accurate OD solutions as well as adequate time for contingency maneuvers following the last burn.

MANEUVER SEQUENCE DESIGNS AND DPTRAJ SIMULATIONS

In the design of the orbit transfer maneuver sequence, several key points and issues were considered. For example, to minimize the number of burns and promote efficiency, the need to perform a posigrade burn after the last retro burn must be avoided. This could be achieved by adopting a "shoot-short" strategy in the maneuver design. Also, the baseline design must prove its ability to handle 2-σ Δv errors (±6%) easily with tweaks and optimization of subsequent burns.

The first posigrade burn would be a calibration burn for the determination and verification of thruster performance, and the Δv was set to 0.1 m/sec. It was determined that two more posigrade burns would be sufficient in achieving the desired drift rate. The first retro burn would be executed at the first opportunity of fixed yaw, flying backward mode to maximize the usage of the 10-day window available for the completion of all retro burns. It was desirable to remove most of the drift rate with a large retro burn in the first maneuver, which could be split into two burns, one orbit apart. Then, the next two retro burns could remain small, leaving ample room for tweaking and absorption of Δv errors.

The last two retro burns were affected by a loose design constraint imposed by the scheduling of TDRSS coverage for tracking purposes. Towards the end of the mission as the satellite neared the target longitude, it was necessary to fine-tune the maneuvers in order to 1) achieve the target ground track spacing and 2) reduce the drift rate to zero. The 2 control parameters for these 2 target constraints were the Δv magnitude and the time of command. However, due to plans to schedule TRDSS coverage for only 2 hours per burn (one orbit ≈ 1 hr 52 min), little room was available for tweaking the time of command. Furthermore, the available tweaking in the time of command was reserved for the optimization of the burn centroid time, in order to reach frozen status in the final orbit. This supported the need to maintain a low drift rate after the first retro maneuver such that the satellite would still arrive within the ±1 km boundary of target without tweaking the time of command of the last two burns.

In the design of the maneuver sequence, the drift rate was calculated based on existing data obtained from DPTRAJ simulations performed during the preliminary trade study on Δv requirements. From those runs, the discrete samples of change in drift rate ($\Delta\dot{\lambda}$) versus Δv were obtained. The DPTRAJ-based $\Delta\dot{\lambda}$ versus Δv contained higher-order effects and was thus more accurate than the analytical linear function given in Figure 2. During the maneuver design, $\Delta\dot{\lambda}$ was obtained with linear interpolation between the discrete data points. Since the higher-order effects were time-dependent and with the linear interpolation of a slightly non-linear system, the time-invariant $\Delta\dot{\lambda}$ obtained from DPTRAJ-based data would contain small errors. Thus, all maneuver designs were verified and fine-tuned with DPTRAJ simulations to produce the final burn sequence.

Baseline Design

The baseline maneuver sequence was designed with the design strategy described thus far. The total Δv was 0.84 m/sec. There were 4 days for contingency maneuvers after the last retro burn.

Table 6. Baseline Maneuver Design

Burn	Date	Δv (m/sec)	Coast (days)	Total coast (days)	Drift rate (km/day)	Drift (km)	Total drift (km)
1	8/15	0.1	4	4	1.620	6.48	6.48
2	8/19	0.159	4	8	4.200	16.80	23.28
3	8/23	0.159	18	26	6.779	122.02	145.30
4a	9/10	-0.125	0	26	4.753	0.74	146.04
4b	9/10	-0.125	3	29	2.727	8.18	154.22
5	9/13	-0.095	3	32	1.188	3.56	157.79
6	9/16	-0.073	4	36	0.000	0.00	157.79

DPTRAJ Simulations for the Baseline Design

DPTRAJ runs were executed for the full set of start and stop drift maneuvers based on the baseline design. The simulation results included:

1. The TOPEX predicted ground track at ascending equator crossings, which showed the difference between the longitude at the equator crossing and the reference longitude with respect to time (similar to Figure 7).
2. A close-up view of the TOPEX predicted ground track at ascending equator crossings after the last two stop-drift burns, which showed the difference between the longitude at the equator crossing and the new, post transfer reference longitude with respect to time (similar to Figure 10).
3. The changes in sma throughout the drift phase using baseline maneuver design (similar to Figure 8).

Design with Max Δv Constraint of 0.15 m/sec

Once the calibration burn was executed, better predictions of thruster performance would be available. If a need arises from the post-burn analysis to impose a constraint on the maximum Δv, the baseline maneuver design could be replaced by the following burn sequence if a maximum Δv constraint of 0.15 m/sec were applied. The total Δv was 0.76 m/sec, and 2 days were available for contingency maneuvers after the last retro burn. Note that delaying the first retro burn was preferred over adding another posigrade burn.

Table 7. Design with Max Δv Constraint of 0.15 m/sec

Burn	Date	Δv (m/sec)	Coast (days)	Total coast (days)	Drift rate (km/day)	Drift (km)	Total drift (km)
1	8/15	0.1	4	4	1.620	6.48	6.48
2	8/19	0.14	4	8	3.890	15.56	22.04
3	8/23	0.14	20	28	6.160	123.21	145.25
4a	9/12	-0.11	0	28	4.378	0.68	145.93
4b	9/12	-0.1	3	31	2.758	8.27	154.21
5	9/15	-0.097	3	34	1.187	3.56	157.77
6	9/18	-0.073	2	36	0.000	0.00	157.77

Contingency Plan with Max Δv Constraint of 0.1 m/sec

The following burn sequence would be the new maneuver design if a maximum Δv constraint of 0.1 m/sec were imposed. The total Δv was 0.78 m/sec. There were 3 days for contingency maneuvers after the last retro burn.

Table 8. Contingency Plan with Max Δv Constraint of 0.1 m/sec

Burn	Date	Δv (m/sec)	Coast (days)	Total coast (days)	Drift rate (km/day)	Drift (km)	Total drift (km)
1	8/15	0.1	4	4	1.620	6.48	6.48
2	8/19	0.1	2	6	3.240	6.48	12.96
3	8/21	0.1	2	8	4.860	9.72	22.68

4	8/23	0.091	19	27	6.334	120.34	143.02
5a	9/11	-0.1	0	27	4.714	0.74	143.76
5b	9/11	-0.1	3	30	3.094	9.28	153.04
6	9/14	-0.094	3	33	1.571	4.71	157.76
7	9/17	-0.097	3	36	0.000	0.00	157.76

ΔV ERROR ANALYSIS

A 2-σ, ±6% Δv error analysis of worst case scenarios was performed to determine the robustness of the baseline design. For example, consistent under and over-burns in the posigrade and retro maneuvers, respectively, would yield the worst case for undershoot. Vice versa, consistent over and under-burns in the posigrade and retro maneuvers, respectively, would yield the worst case overshoot. All other combinations of under and over-burns would fall within the two extremes of worst case undershoot and overshoot. Thus, only the worst case scenarios needed to be analyzed.

During the operation of TOTM, the drift rate and ground track solutions from OD would be used in the re-design of the next Δv. The maneuver execution error with the estimation error included was reflected in the drift rate. Thus, Δv tweaking for error compensation based on the Δv error was equivalent to that based on the drift rate.

In the Δv error analysis, the known and unknown errors were not considered separately. The applied ±6% Δv error was the 2-σ probability of the total Δv error, which was known plus unknown %errors. The 1-σ unknown error with 2-day tracking was approximately 0.8%. It was assumed to be near the level of modeling error, and thus not treated separately. The real concerns were 1) whether the last two maneuvers would have enough room to be tweaked for the known errors, and 2) whether the unknown errors associated with the last two maneuvers would cause the satellite to miss the target ± 1 km deadband. Both points could be addressed by maintaining a low drift rate during the last 2 maneuvers. This resulted in small required ΔVs with plenty of margin for tweaking. Also, small unknown errors on a low drift rate would not cause large shifts in the targeting. Thus, emphasis was placed on achieving a low drift rate via a large, first retro maneuver.

The nominal and four worst-case scenarios were examined. The worst cases included 6% error of 1) over-burns in all maneuvers, 2) under-burns in all maneuvers, 3) over-burns in the posigrade maneuvers and under-burns in the retro maneuvers, and 4) under-burns in the posigrade maneuvers and over-burns in the retro maneuvers. The first commanded Δv was 0.1 m/sec. With a +6% error, for example, the achieved Δv for the first burn became 0.106 m/sec. Adjustments to burns 2 through 6 were then made to compensate for this over-burn in the first maneuver. The commanded Δv for the second burn was reduced to 0.155 m/sec. A +6% error was then applied to the second maneuver, and this process was continued until the commanded Δv for the last burn had been determined. In the worst cases analyzed, the satellite consistently arrived within the +/- 1 km boundaries of the target longitude. This demonstrated the robustness of the maneuver design. The OMM ΔVs to correct for errors in the last burn determined from quick estimates were less than 10 mm/s. The maximum Δv could potentially be 0.171 m/sec in the third burn, to compensate for under-burns in the first 2 maneuvers. In the process of adjusting the subsequent ΔVs for error compensation, the burn magnitudes would begin to deviate from the baseline values. The effects could be compounded as the maneuvers were executed, and large departures from the baseline could result in the last 2 retro burns for the worst-case scenarios. This illustrated the need to supply a generous margin for tweaking the ΔVs in the last 2 retro burns.

OPTIMIZATION OF BURN CENTROID TIME

One of the objectives in the tandem mission was to achieve frozen status in the final orbit per science requirement. The ground track during the 10-day cycle would remain a repeat pattern if the eccentricity (e) and argument of perigee (ω) were:

$$e = 95 \times 10^{-6} \pm 50$$

$$\omega = 90 \pm 30 \text{ deg}$$

excluding combinations of extreme values (ref. 4). This frozen orbit envelope is shown in Figure 6.

Before the maneuvers, e and ω were located in the lower right corner of the first quadrant near the boundary of the frozen orbit envelope as shown in Figure 4. The changes in the e and ω depended on the location in the orbit at which the burn was executed; e.g., the true anomaly of the burn centroid time. Figure 4 shows the predicted post-burn e and ω obtained via Equations (5) and (8), with burn opportunities plotted at every 5° in true anomaly ranging from 0° to 360°. From such plot, the effect of the burn centroid time on the e and ω was readily available to aid in the maneuver design.

The posigrade burns would be executed during yaw steering, and spacecraft thermal/power issues associated with the turn-burn-turn maneuvers must be considered. To minimize the turning angle and considering other spacecraft issues, the posigrade burns would be scheduled to occur at orbit midnight. Unfortunately, this was near the worst point of burn centroid time for the pre-TOTM e and ω, as shown in Figure 4, and would take the orbit out of the frozen orbit envelope. The second and third posigrade burns would cause an even further departure of the orbit from the envelope as shown in Figure 6. To stop drift, the retro burns were executed during fixed yaw where the satellite was required to turn only up to 12° in the turn-burn-turn maneuvers. Therefore, the burn centroid times for the retro burns were less constrained and could be optimized in order to bring the orbit back towards the envelope. By no coincidence, the optimal burn centroid times for the retro burns were near orbit midnight, which was favorable for spacecraft issues. As shown in Figure 6, the execution of the retro maneuvers at the optimized burn centroid times would only bring the orbit back to the edge of the envelope. The e and ω then wondered about the boundary during the 30-day, post-burn period and eventually migrated back inside the envelope. However, if the thruster performance and actual burn centroid times during the retro burns were off-nominal, the orbit could easily remain in exile from the envelope. Thus, OMM(s) could be required for returning the orbit back to frozen status. Note that if the pre-TOTM e and ω were in the third quadrant of the envelope (instead of first quadrant), executing the posigrade burn at orbit midnight would be desirable since the orbit would be moved towards the center of the envelope, and much of the aforementioned concerns would be non-issues.

An example of the centroid time optimization is given in Figure 5 for maneuver 5. The pre-burn e and ω were 0.000136 and 136.66°. A commanded Δv of -0.095 m/sec would change the e and ω as shown in Figure 5. The optimal burn centroid was at the true anomaly associated with the point closest to the frozen orbit envelope, with a slight bias favoring the eccentricity. The resulting e and ω from DPTRAJ simulation display a slight offset from the predicted values due to non-linear, time-dependent, higher-order effects unaccounted for in the analytical equations. In like manner, the optimum burn centroid times were chosen for the last 2 maneuvers.

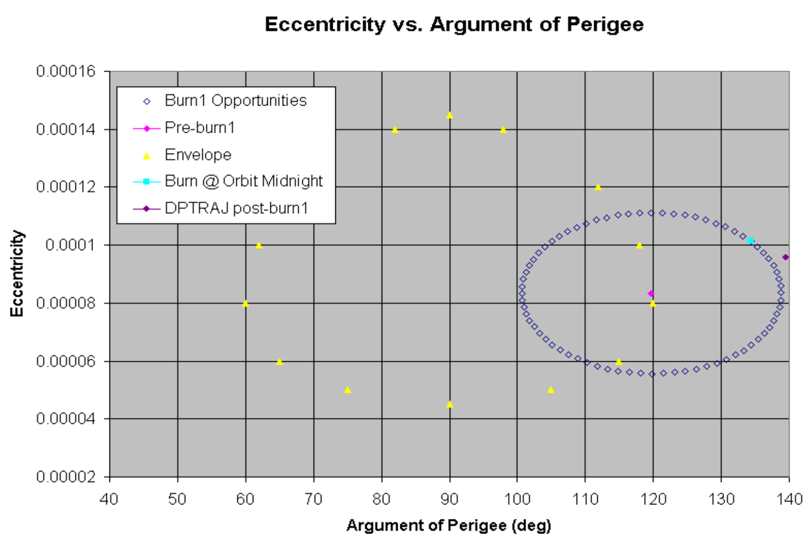

Figure 4. Predicted Frozen Orbit Status for Burn 1 Executed at Orbit Midnight

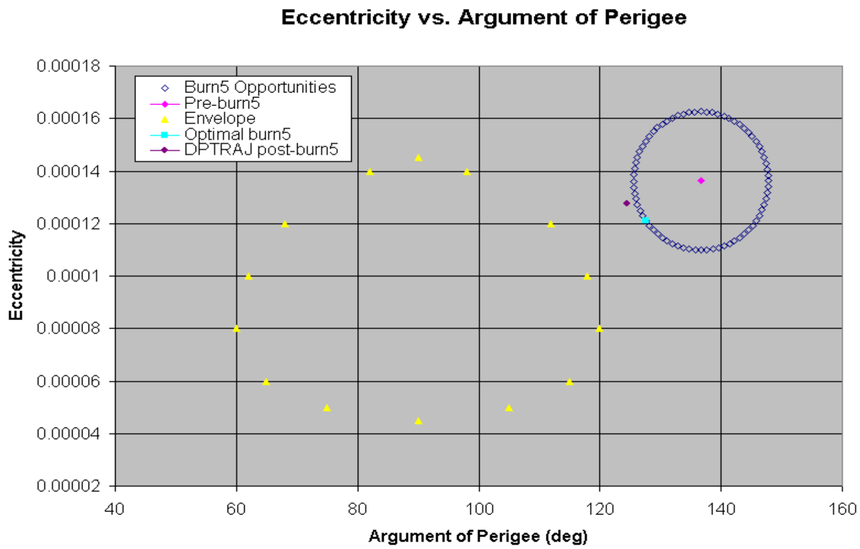

Figure 5. Optimization of Burn Centroid Time for Maneuver Five

DPTRAJ SIMULATIONS WITH OPTIMIZED BURN CENTROID TIMES

In order to re-achieve frozen orbit status after the series of maneuvers, the NAVT was responsible for picking the burn centroid times for the 3 retrograde burns. This would allow optimization of the orbital locations where the burns were executed, bringing the e versus ω back inside the "frozen orbit envelope" (Figure 6).

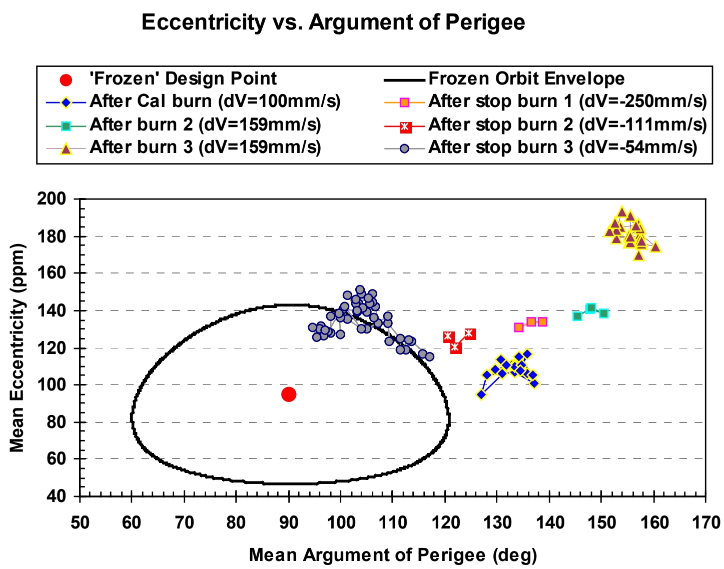

Figure 6. Frozen Orbit Status Throughout Series of Burns, Using Baseline Maneuver Design

RESULTS OF TOTM MISSION OPERATION

The TOTM mission operation extended from 15-Aug-02 to 16-Sep-02 as planned. The commanded tweak Δv, achieved Δv, and %error are given in Table 9 (ref. 5). Note that maneuvers 4a and 4b were evaluated as a single burn. The Δv errors ranged from –2.48% to 2.45%, well within the design values of ±6% in the Δv error analysis.

Table 9. Results of TOTM Mission Operation

Maneuver	Date (2002)	Time (UT)	Commanded Δv (mm/sec)	Achieved Δv (mm/sec)	Error (%)
1	Aug 15	19:10	100.0	101.64	1.64
2	Aug 19	18:47	159.0	162.9	2.45
3	Aug 23	18:20	153.0	152.84	-0.11
4	Sep 10	17:27, 21:09	-260.0	-253.55	-2.48
5	Sep 13	20:18	-100.0	-99.84	-0.16
6	Sep 16	19:26	-57.0	-57.06	0.11

The ground track and change in semi-major axis during the mission operation according to tracking data are given in Figure 7 and Figure 8. Note that TOTM_CAL, TOTM_D231, TOTM_D235, TOTM_253, TOTM_256, and TOTM_259 are maneuvers 1 through 6, respectively.

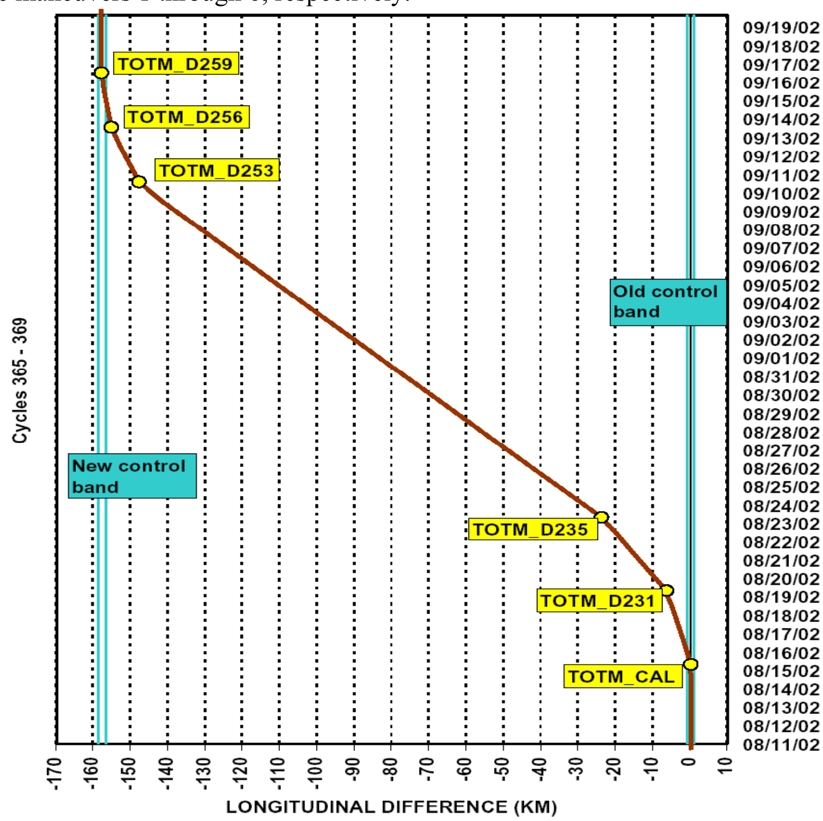

Figure 7. TOPEX Observed Ground Track at Ascending Equator Crossings During TOTM Campaign

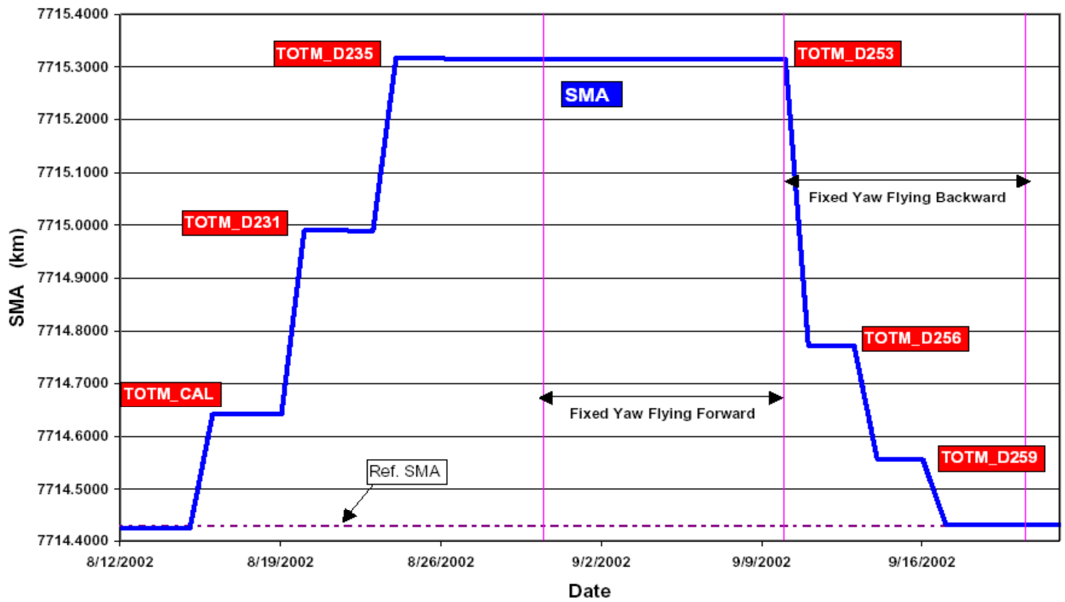

Figure 8. Observed Mean Semi-Major Axis

The evolution of the orbit during the mission operation relative to the frozen orbit envelope according to tracking data is given in Figure 9.

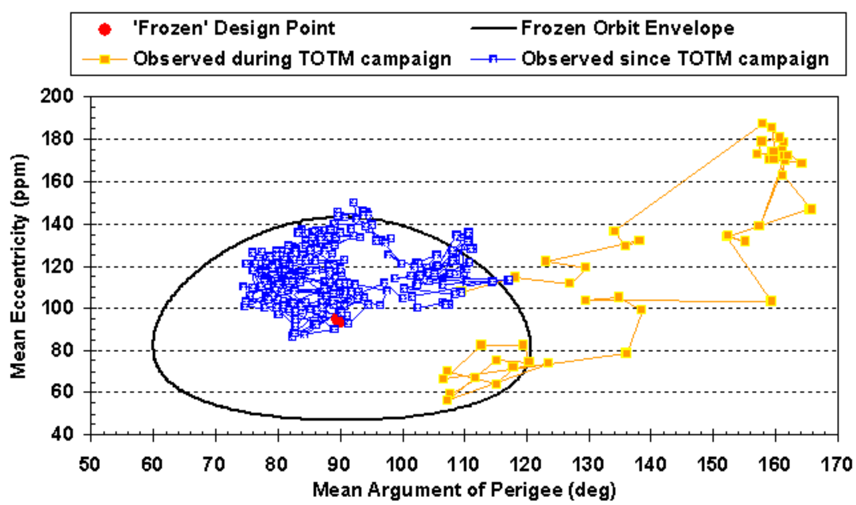

Figure 9. Observed and Projected Eccentricity vs. Argument of Perigee

To push back the date of the first OMM after the TOTM operation, a command was uplinked to TOPEX to switch from orbit decay mode to boost mode (lead/lag strategy) on September 17, 2002, one day after the last retro maneuver (TOTM_D259). That allowed OMM23 to be performed on December 18, 2002, as shown in Figure 10.

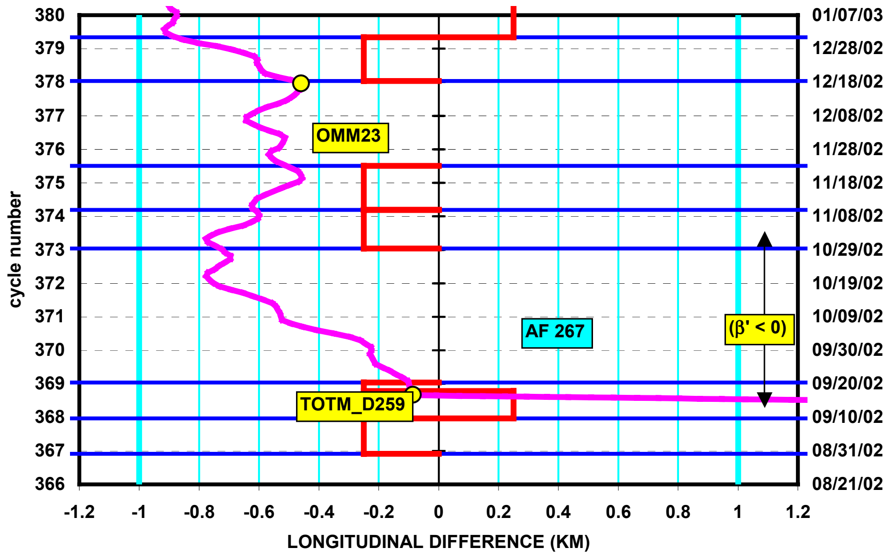

Figure 10. TOPEX Ground Track at Ascending Equator Crossings after Last Retro Burn (New Orbit)

CONCLUSIONS

The results from the series of trade studies and analyses for the TOTM design are summarized below:

1) The design of orbit transfer maneuver sequences produced the following:
   i. The baseline with a maximum Δv of 0.159 m/sec.
   ii. Additional burn sequences with maximum Δv constraints of 0.15 and 0.1 m/sec.
2) Δv errors would be compensated for by tweaking and optimizing subsequent burns. A Δv error in the last burn could be compensated for by an OMM as needed.
3) Δv re-design for error compensations would be based on the ground track spacing and drift rate provided by mean elements (NAVT solutions) as the primary source, with EPV (FDF) and GPS fast OD as additional references.
4) To achieve frozen orbit, the burn centroid times for all the retro burns would be optimized and set by NAVT.

The results of the TOTM mission operation are summarized below. All the objectives of the TOTM mission were achieved.

1) Six maneuvers were executed with Δv errors ranging from –2.48% to 2.45%. The fourth maneuver was split into 2 burns but evaluated as one.
2) TOPEX had successfully acquired a new orbit which repeats ground tracks midway between two adjacent JASON-1 tracks.
3) Frozen orbit was achieved.
4) The first OMM following TOTM was performed on December 18, 2002.

ACRONYMS AND SYMBOLS

a	Semi-major axis
ACS	Attitude Control System
CNES	Centre National d'Etudes Spatiales
DPTRAJ	Double Precision Trajectory
Δv	Delta-v
e	Eccentricity
EPV	Extended Precision Vector
f	True anomaly

FDF	Flight Dynamics Facility
GPS	Global Positioning System
γ	Pitch angle
i	Inclination
M	Mean anomaly
n	Orbit rate
NASA	National Aeronautics and Space Administration
NAVT	Navigation Team
OD	Orbit Determination
OMM	Orbit Maintenance Maneuver
Ω	Argument of the ascending node
ω	Argument of perigee
r	Radial distance of satellite
SLR	Satellite Laser Ranging
sma	Semi-Major Axis
TOTM	TOPEX/Poseidon Orbit Transfer Maneuver
u	Argument of latitude
ψ	Yaw angle

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